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NuMI Repair-cell Shielding Design

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Introduction

The NuMI repair-cell[1-4] (Figs. 1,2,3) is designed to be used for inspection, simple repairs or replacement of the beam focusing horns or the target.[4] The repair-cell will be constructed at the downstream end of the target hall.[5] The design goal is to have the dose rate outside the repair-cell from all sources (repair-cell and its content) to be less than 10 mrad/hr. This note combines and summarizes the different shielding calculations that were done for the design of the repair-cell.

Through out the following sections the dose rates for selected parts of the repair-cell are given for a range of thicknesses. This is intended to be useful for assessing dose rates, if needed, for cases where there are non-uniformities in the shielding. An example would be the recesses in the concrete blocks where the lifting hooks are located. The summary at the end gives the results for the design values.

Methodology

The dose rate information was taken from the MARS calculations paper.[6] The first horn is very close to the target and it will have the highest level of residual radioactivity. All the calculations have been done for the horn1 parameters.[5,6]

The NuMI target[4], after one month of irradiation and one day of cooling will be about 10 times more radioactive than the body of the horn1[6]. The target is mainly made of carbon with some small amount of aluminum and stainless steel for the cooling lines and the vacuum shield. Because of the carbon, after one year of irradiation and one week of cooling, the dose rate will be 2.8 times higher than that of one-month one-week irradiation and cooling[7]. However, because of the small dimensions of the target and that the dose outside the shield is mainly due to ^{7}Be (0.477 MeV photon), the dose rates outside the shielding are comparable to those of horn1. It should be noted that the repair-cell would be used only for target replacement, not for target repairs.

It is assumed for the calculations that the horn has been operating for one year and allowed to cool down for one week. The one-week cool down is reasonable; given all the required preparatory work involved for handling a highly radioactive horn.[2,3] Table 1 gives the residual activity levels for the different parts of the horn. The 1 MeV photon attenuation lengths and buildup factors are used in all the calculations. Given the variety of residual radionuclides, 1 MeV is a reasonable average for the photon energies involved. The assumption of one-month irradiation instead of one-year will not result in a significant reduction in the residual activity levels of the horn. The horn has been modeled as an extended source composed of three parts: two solid cylindrical disks (end flanges) and one hollow cylindrical surface source with a diameter[1] of 13.75". The horn is placed at the center of the repair-cell, which is 56" wide, 21 ft. long and 163" high.[4]

On Contact Dose Rates after T_i, T_c (Rad/hr)	US flange	Body	DS flange
1 month, 1 day	800	600	1200
1 year, 1 week	160	120	240
1 month, 1 week	21	16	32

Table 1. Residual dose rates of the horn1 after the irradiation time of T_i and cooling time of T_c, for the beam upstream (US) flange, cylindrical body and the down stream (DS) flange, respectively.

Results

In the following sections the shielding calculations and the results for the repair-cell walls, door, roof, windows and the gaps in the walls and the roof are described.

A. I. Concrete, iron and lead bricks for the side Walls

The dose rate from a cylindrical surface source at a point, P, behind a shield wall (Fig. 4) is given by the expression

$$\dot{D} = \frac{S_A}{4} R \int_0^H dz \int_{-\pi}^{\pi} \frac{e^{-\mu y}\, d\varphi}{R^2 + a^2 - 2aR\cos\varphi + z^2},$$

Where $y=y(\varphi,z)$ is the thickness of the shield measured from the elementary area dS towards P given by

$$\mu y = b_1 \frac{\sqrt{R^2 + a^2 - 2aR\cos\varphi + z^2}}{a - R\cos\varphi}.$$

After the following substitutions for the geometrical parameters given in figure 4,

$$k = \frac{H}{R}, \qquad p = \frac{a}{R},$$

results can be summarized as

$$\dot{D}(rad/hr) = B\frac{S_A}{2} W(k,p,b_1),$$

where b_1 is the shield thickness expressed in mean free path lengths.
μ is the photon attenuation coefficient of the material,
S_A is the specific activity of the surface source,
B is the buildup factor for 1 MeV photons in the shield material
$W(k,p,b_1)$ is an integral function[8-13], which is evaluated numerically for different values of k, p and b_1.

The methodology for other material and configurations (with and without a shield) are similar. For other extended source geometries, other kinds of non-analytic integrals will result. The expressions for other locations behind the shield are obtained by means of the additivity rule. The details for other cases are discussed in references,[8-14] only the results for the cylindrical horn will be given here.

The east and west walls are constructed from 3 ft. thick concrete blocks. The east wall has several lead-glass windows, in steel frames, with lead bricks stacked around them. The calculated dose rates are given in table 2. As the results show, 3 ft. of concrete is sufficient to reduce the dose rates to less than 1 mrad/hr. The steel, lead bricks and lead-glass will be discussed in the following sections.

Thickness (in)	DS flange (mrad/hr)	Body (mrad/hr)	US flange (mrad/hr)	Total (mrad/hr)	Material
1.97	320.80	160.40	213.87	695.07	Lead
3.94	6.08	3.04	4.06	13.18	
6.01	0.09	0.04	0.06	0.19	
8.07	0.00	0.00	0.00	0.00	
6.01	39.45	19.72	26.30	85.47	Iron
8.07	3.73	1.86	2.49	8.08	
9.06	1.19	0.59	0.79	**2.58**	
12.01	0.04	0.02	0.02	0.08	
24.00	0.00	0.00	0.00	0.00	
36.00	0.00	0.00	0.00	0.00	
24.00	6.24	3.12	4.16	13.52	Concrete
30.00	0.66	0.33	0.44	1.43	
33.00	0.21	0.11	0.14	0.46	
36.00	0.07	0.03	0.05	**0.15**	

Table 2. Dose rates on contact outside the repair-cell wall made of different material and thicknesses.

B. II. Lead-glass Windows

In addition to TV cameras, windows are also planned for an easy and quick inspection of the horns[4]. The thickness of the lead glass windows is chosen to reduce the dose rates immediately outside the window to less than 10 mrad/hr.

Lead glass is salvaged from an old Fermilab experiment[15] (E705). Its density is 4.08 g/cc. Table 3 gives the composition of this lead glass. The second column gives the overall percentage by weight of each compound. Column 3 gives the percentages of the Pb, Si, K and Na, and column 4 gives the percentage of oxygen in each compound, respectively.

Compounds	%W(comp.)	%W(w/o oxygen)	%W(oxygen)
PbO	55.4	53.34	2.06
SiO_2	38.3	24.40	13.90
K_2O	5.2	4.72	0.48
Na_2O	1.1	0.94	0.16

Table 3. Composition of the lead glass in percentages of the weight.

To calculate the lead glass attenuation, the attenuation of the individual elements was added together, weighted by their fractional weights,

$$\lambda_{leadglass} = \sum_i \lambda_i w_i$$

where, λ_i is the gamma ray attenuation for the element i of the compound. The values for these attenuations were obtained from the NIST database[16]. As for all other shielding calculations of the repair-cell, the gamma ray energy was assumed to be 1 MeV. Table 4 gives w_i and λ_i used for the calculation of $\lambda_{leadglass}$. A is the atomic weight of the element.

Element	%Weight	A	λ(cm^2/g)
O	16.61	8.00	6.37E-02
Pb	53.34	207.20	7.10E-02
Si	24.40	28.09	6.36E-02
K	4.72	39.10	6.22E-02
Na	0.94	23.00	6.10E-02

Table 4. Lead-glass composition and attenuation coefficients for 1MeV gammas.

The resulting mass attenuation coefficient of this lead glass, for 1MeV gamma rays, is 6.67×10^{-2} cm^2/g. The repair-cell window will have an 18"x18" opening made of six 6"x6"x18" pieces of lead glass. This configuration will make a 12" thick window. The lead glass is recessed by 1" from the inner face of the repair-cell wall. With no other sources of radiation nearby, dose rates from different parts of the horn at different distances are given in table 5. Columns 4 and 5 give the contact dose rates to an observer at the outer face of the window and the wall, respectively.

Source term	(Rad/hr)	Dose rate at outer face w/o window (Rad/hr)	Dose rate at outer face with window (mrad/hr)	Dose rate at outer WALL with window (mrad/hr)
DS flange	240	25.9	9	7
Body	120	9.3	3	2
US flange	160	17.3	6	4

Table 5. Dose rates outside lead-glass windows.

These dose rates are acceptable for the types of work that is expected to be done around the repair-cell.

C. III. Lead bricks for the north window

In order to be able to access the horn from the back iron wall or the side window ports, lead bricks are used as a mobile shield, which can be stacked to open up a small access port to the horn. The required lead shielding for the east or west walls is given in section I. In this section the lead shielding required for a circular cylindrical flange facing the north door is calculated.

The required lead shielding for the north window was calculated by modeling the down stream flange as a circular cylindrical source, located 3.25 feet from the lead shield.

$$\dot{D}(rad/hr) = B\frac{S_A}{2}\left[E_1(b_1) - E_1(b_1 \sec\theta)\right]$$

S_A is the specific activity of the surface source,
B is the buildup factor for 1 MeV photons in the shield material
b_1 is the shield thickness expressed in mean free path lengths.

$$\sec\theta = \frac{\sqrt{R^2 + a^2}}{a}$$

R is the radius of the disk
a is the distance from the disk source,
E_1 is the first of a family of exponential integral functions, which is computed numerically.[8-13]

The combined doses from the upstream and downstream flanges are given in Table 6. The partial shielding of radiation of one flange by the other one is not included.

	TOTAL Dose Rate (contact)		TOTAL Dose Rate (at 1ft.)	
Pb shield Thickness (in)	Reverse horn (mrad/hr)	At North wall (mrad/hr)	Reverse horn (mrad/hr)	At North wall (mrad/hr)
4.1	3.35	4.73	2.19	3.02
5.5	0.28	0.39	0.18	0.25

Table 6. The dose rates from a radioactive horn at the north wall with two different thicknesses of lead shielding. The dose is also given for the improbable case when the horn is turned around.

D. IV. Gaps in Concrete walls

Due to the non-uniformity of the concrete shielding blocks, there is a possibility that cracks could exist between the blocks, which could allow the gamma radiation from a hot horn to stream through. In order to assess the radiological implication of such cracks or gaps, gaps are modeled as rectangular penetrations through the three feet of concrete shielding blocks.[8,14] In reality the end flanges are self-absorbing cylindrical-ring volume-sources. For the gap calculations the horn flanges are assumed to be cylindrical surface sources (Fig. 4, without the shield) with the correct dose rates predicted by MARS.
The dose from a cylindrical surface source without a shield is used to calculate the source term at the entrance to the gaps.

$$\dot{D}(rad/hr) = \frac{S_A R}{(a+R)} F(\varphi, k),$$

$$\varphi = \arctan\left(\frac{H}{a-R}\right) \quad , \quad k = \frac{2\sqrt{aR}}{a+R}$$

S_A is the specific activity of the surface source,
a is the distance from the center (axis) of the cylinder,
R is the radius of the cylinder (horn body),
H is the length of the horn,
φ is the half angle subtended by the source at the gap,
F is called the secant integral function or the Sievert integral, which is computed numerically.[8-13]

Since the horn is at a distance from the walls, there is further attenuation with distance. For this attenuation the distance of the entrance to the gap from a cylindrical surface source is assumed. Table 7 below gives the expected dose rates from different parts of the horn, at the gap entrance.

Source	Dose on Contact (Rad/hr)	Dose rate at the gap (Rad/hr)
DS flange	240	50.5
Body	120	18.9
US flange	160	33.7

Table 7. Last column gives the expected dose rates from horn1 used as the source for the gaps calculations.

Three crack widths and three crack heights were used for modeling the wall gaps. Table 8 shows the results of the calculations. Since the gaps are relatively narrow and long, the scattered component of the radiation is negligible (a few percent[14]). Only the direct (line of sight) component is considered here.

Gap Dimension			Dose Rate (on Contact) (mrad/hr)			Dose Rate (at 1ft) (mrad/hr)		
Width (in)	Length (in)	Depth (ft)	DS	Body	US	DS	Body	US
0.4	12	3	28.5	10.7	19.0	16.1	6.0	10.7
0.2	12	3	14.2	5.3	9.5	8.1	3.0	5.4
0.1	12	3	7.1	2.7	4.7	4.0	1.5	2.7
0.4	8	3	19.1	7.2	12.7	10.8	4.0	7.2
0.2	8	3	9.6	3.6	6.4	5.4	2.0	3.6
0.1	8	3	4.8	1.8	3.2	2.7	1.0	1.8
0.4	4	3	9.6	3.6	6.4	5.4	2.0	3.6
0.2	4	3	4.8	1.8	3.2	2.7	1.0	1.8
0.1	4	3	2.4	0.9	1.6	1.4	0.5	0.9

Table 8. Expected dose rates from gaps in the wall shielding.

Since the repair-cell design goal is a typical dose rate of 10 mrad/hr outside the cell, as seen from Table 8, gaps wider than 0.2 inches should be filled or maybe shimmed as much as it is practical.

E. V. Iron Door and the north wall

The end flanges become more radioactive than the body of the horn. The flanges are modeled as two solid cylindrical disks facing the iron door and the north iron wall at different distances. Similar methodology as in section III was used for the shielding effectiveness of the iron doors. The calculated dose rates are given in Table 9.

Iron shield Thickness (in)	TOTAL	
	South door (mrad/hr)	North wall (mrad/hr)
9.0	0.66	0.93
10.0	0.22	0.31
10.5	0.13	0.18
11.0	0.07	0.10
12.0	0.02	0.03

Table 9. Dose rates outside the iron door and the north iron wall of the repair-cell.

The angle between the edge of the repair-cell opening and the edge of the iron door should give at least 2.3ft of equivalent concrete shielding. On each side, the door width has to extend past the inside opening of the repair-cell by about 2 ft (of course the iron door thickness can be stepped down at an approximate 45 degree slant).

F. VI. Iron Roof

Calculations for the shielding on top of the repair-cell are similar to that done for the wall, except it is assumed that the roof is 9 ft. above the cylindrical axis of the horn. The combined dose from different parts of the horn is given in Table 10.

Thickness (in)	DS flange (mrad/hr)	Body (mrad/hr)	US flange (mrad/hr)	Total (mrad/hr)
8.46	0.99	0.49	0.66	2.14
9.06	0.50	0.25	0.33	1.09
9.45	0.32	0.16	0.21	0.69
10.04	0.16	0.08	0.11	0.35
10.43	0.10	0.05	0.07	0.22
11.02	0.05	0.03	0.03	0.11
12.01	0.02	0.01	0.01	0.03

Table 10.Total dose rates on top of the iron roof of the repair-cell for varying thicknesses of iron.

G. VII Gaps in the Iron Roof

The steel plates that provide radiation shielding over the top of a horn or target/baffle module when it is in the repair-cell are flame cut. The edges of the plate are not flat, which might leave cracks as large as 1-inch wide between covers. These cracks will be perpendicular to the horn or target axes (beam direction) and would look directly down on the target or horn, although from some considerable distance. To calculate the dose rate leaking through it, it is assumed that the gap depth is 9 inches, which is about the same as the thickness of the CCSS shielding used for the roof. It was also assumed that the gaps are half as long as the width of the repair-cell. Since one continuous one-inch gap means the plates can be pushed together further, this is a reasonable assumption. Calculations are the same as the section IV calculations. The results are given in Table 11.

Source term	(Rad/hr)	Dose rates at gap entrance (Rad/hr)	Dose rates at gap exit (mrad/hr)	Dose rates with 5" iron shield (mrad/hr)
DS flange	240	15.4	458.7	7.4
Body	120	5.5	163.5	2.7
US flange	160	10.3	305.8	5.

Table 11. Dose rates due to different parts of the horn leaking through a gap are given in the forth column. Dose rates after 5" of iron shielding are given in the last column.

Since the roof shield should be removable, filling the gaps or shimming is not practical. Based on the above results a 5-inch thick and 3-inch wide (to straddle the gaps by one inch) iron piece is needed to reduce the doses to reasonable levels for "limited occupancy" of the workers on top of the repair-cell. The iron piece should be "C" shaped to cover the east and west extensions of the gaps as well, or a few lead bricks can be stacked to cover these side-gaps. Around the places on the roof where the horn module extensions are protruding, a lead blanket or other ALARA measures such as time and distance should be used.

Summary

Table 12 gives a summary of the dose rates at different locations around the repair-cell when an activated horn1 is placed inside it. The thicknesses given are the design values.

Section of the repair-cell	Material	Thickness (inches)	Max. Contact Dose Rate (mrad/hr)	Max. Dose Rate @1' (mrad/hr)
Wall (east)	Concrete	36.00	0.15	0.15
Windows (east)	Lead glass	12.00	9.00	6.00
Windows (east)	Lead	16.00	0.00	0.00
Wall (north)	Iron	12.00	0.03	0.00
Roof	Iron	9.11	1.04	0.65
South door	Iron	12.00	0.02	0.00
Gap in the wall[a]	air	0.2[b]	9.60	5.40
Gap in the roof[a]	Air	1[c]	7.40[d]	2.10[d]
Window (north)	Lead glass	12	8.65	5.48
Window (north)	Lead	8	0.00	0.00
Window (north)	Lead	12	0.00	0.00

[a] For gaps, the dose from the DS flange w is given in this table.
[b] This is the acceptable width of the gap (see text).
[c] This is a conservative gap width for the roof (see text).
[d] With 5" of iron shielding (see text).

Table 12. Summary of the dose rates for different parts of the repair-cell with the design dimensions.

As stated previously, roof gaps need to be covered with a 5-inch thick and 3-inch wide (to straddle the gaps by one inch) iron strip is needed to reduce the doses to reasonable levels for "limited occupancy" of the workers on top of the repair-cell. Gaps greater than 0.05 inches in the roof shielding and wider than 0.2 inches in the concrete walls will result in dose rates larger than 10 mrad/hr outside.

Results of MARS calculations[17] shows that the residual dose rates on top of the concrete shielding on top of the target pit is less than 1 mrad/hr. Based on this results and the location of the repair-cell in the target hall, a significant contribution to the dose from the residual activation of the repair-cell components is not expected. Including the mitigations mentioned for the gaps, the largest dose rates around the repair-cell should be less than 10 mrad/hr at one foot and on contact.

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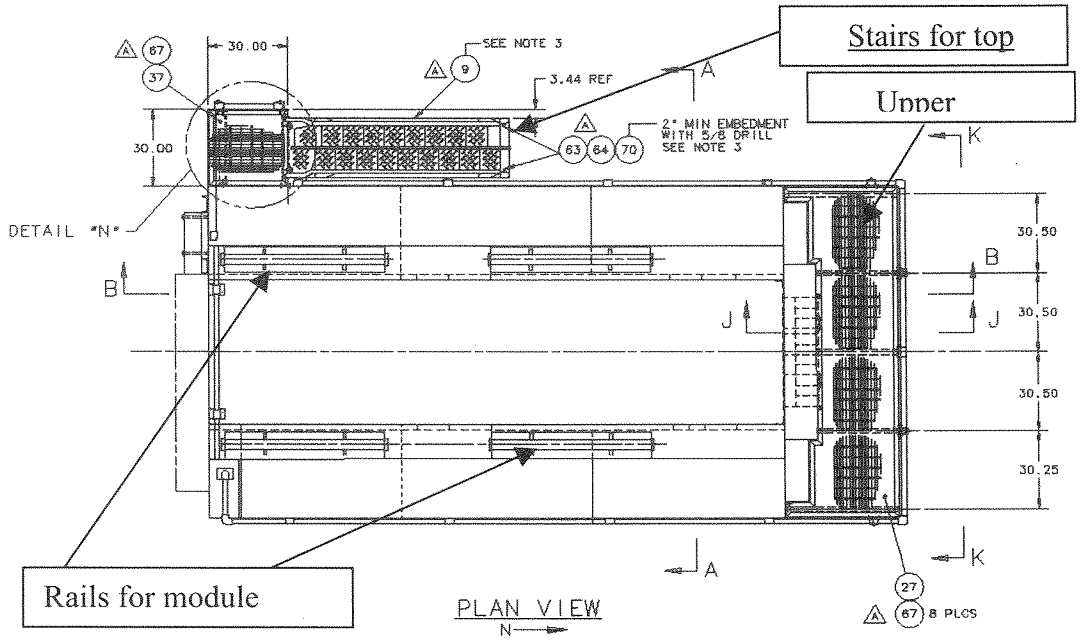

Figure.1. Plan view of the Repair-cell assembly

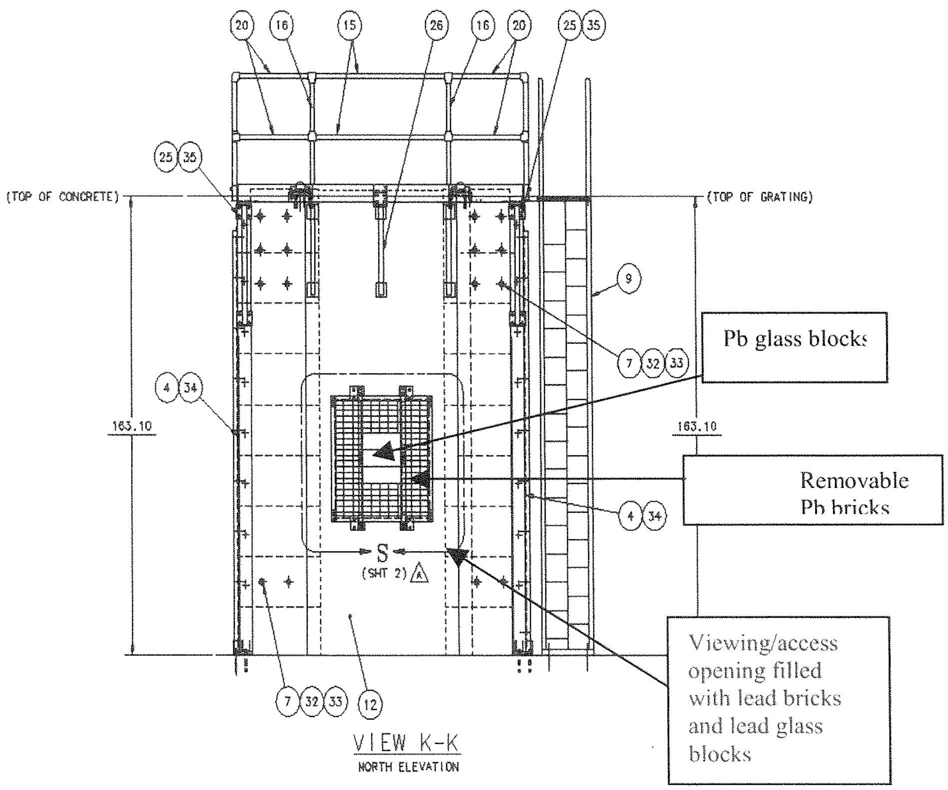

Figure 2. North end elevation view of the Repair-cell assembly.

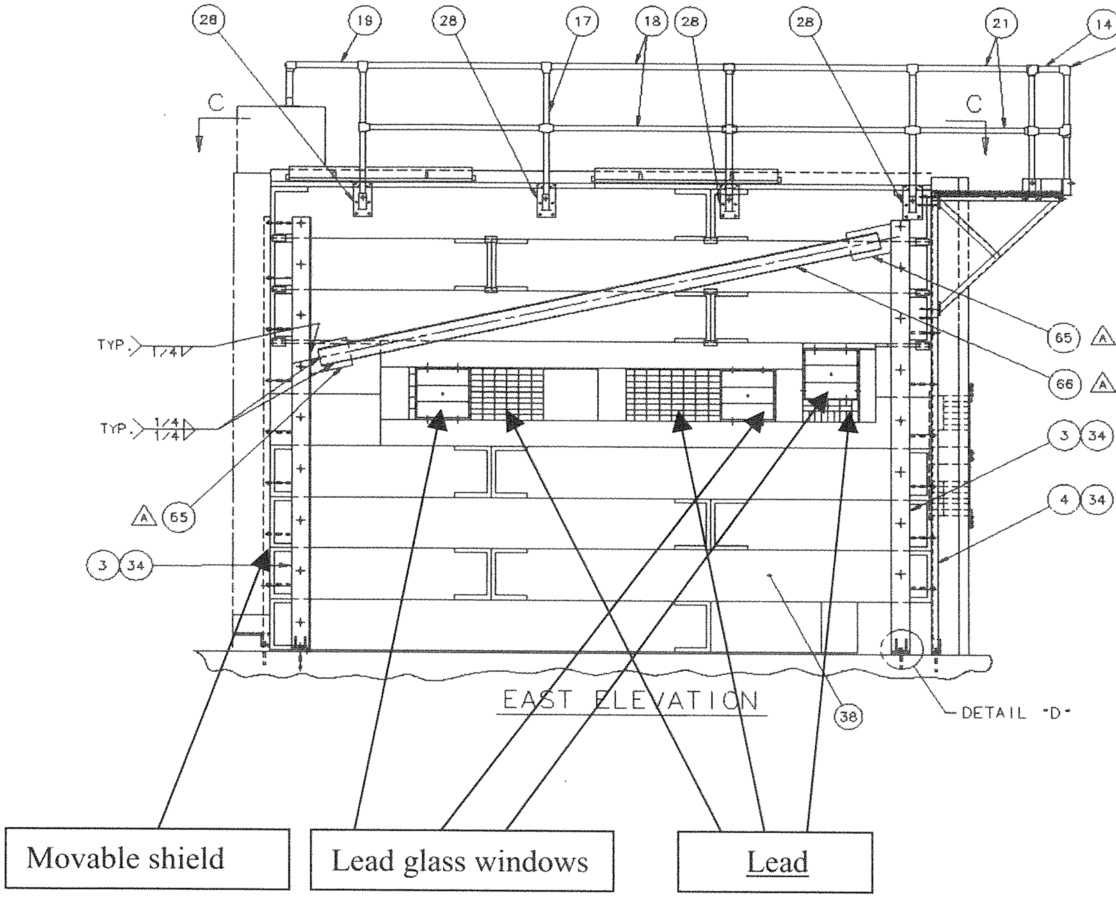

Figure 3. Side elevation view of East wall of Repair-cell.

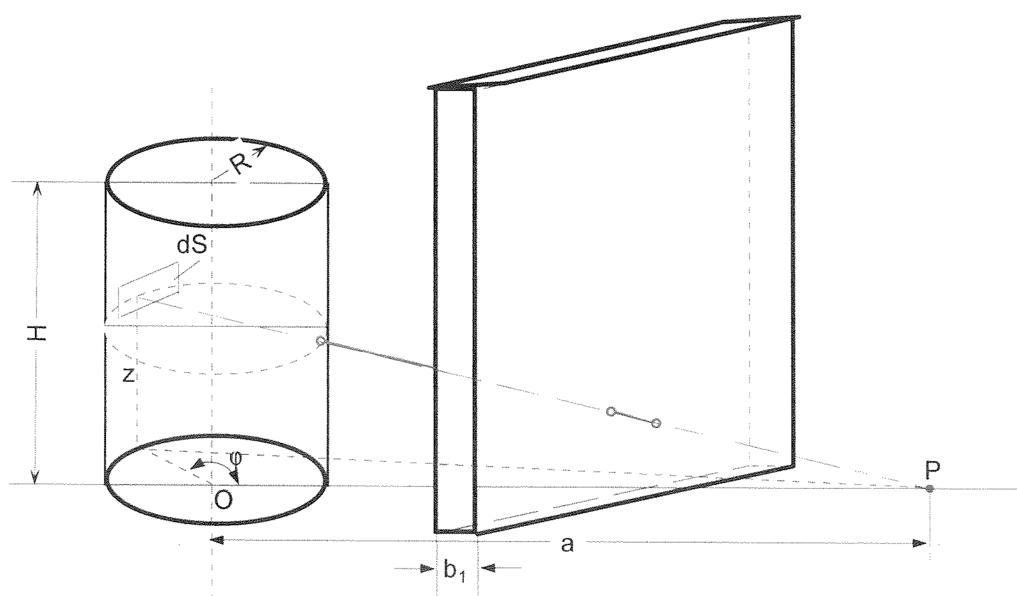

Figure 4. Geometry for a cylindrical surface source with parallel slab shield.